Accelerating the Hierarchical Multi-Scale (HMS) Model by Exploiting Quasi-Homogeneous Subdomains

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Overview of the work

In simulations of material forming processes, macroscopic zones of nearly homogeneous strain response can be observed. We show how in such zones the evolution of material properties at each finite element (FE) integration point can be approximated from the properties at a representative point. This largely reduces the computational cost.

Problem

Hierarchical Multi-Scale (HMS) software [1]:

Features:

- based on physics-based polycrystalline plasticity models
- computation of texture evolution
- approximation of the anisotropy of the plastic properties by analytical plastic potential function
- adaptive reconstruction of the macroscopic material properties
  - after a sufficient change of the crystallographic texture, or
  - when a certain level of accumulated plastic strain is exceeded
- calibration of the anisotropy by means of virtual experiments

Drawbacks to be eliminated:

- updates of the material properties at an FE integration point is computationally intensive
- evolution of the material properties is required at each integration point

$\Rightarrow$ large simulation time

Solution

The simulation time can be reduced by **spatial clustering** the nearly homogeneous sub-domains distinguishable in practical simulations.

- The accumulated plastic strain determines the evolution of the material properties.
- Similar state variables (e.g. crystallographic texture) subjected to a similar deformation history (i.e. the plastic strain) would evolve along nearly identical trajectories.
- Derived macroscopic plastic properties would be similar as well.

Spatial clustering [2] organizes objects into groups whose members are similar w.r.t. some **features of interest** and also distance, **connectivity**, or relative density in the space.

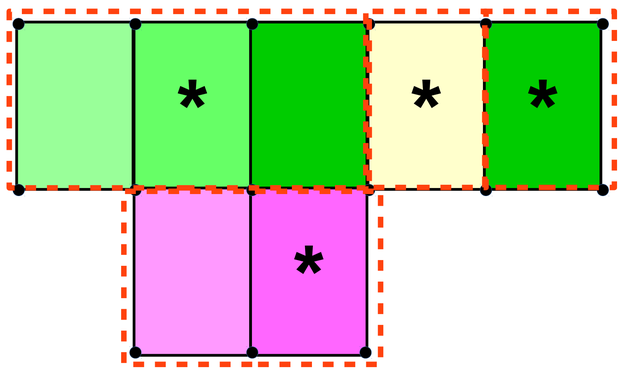

Figure 1: Spatial clustering in an FE mesh. Clusters are bounded by the dotted lines, cluster representatives are labeled with asterisks.

Effects:

- Updates of the material properties occur at a representative integration point per cluster and are propagated to the other members.
- A large reduction in the number of updates is expected.

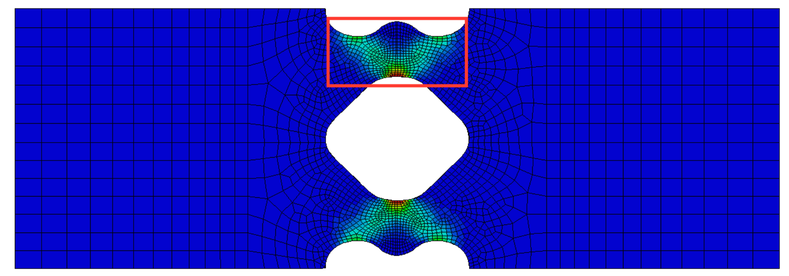

Figure 2: A complex geometry tensile test (field: accumulated plastic strain)

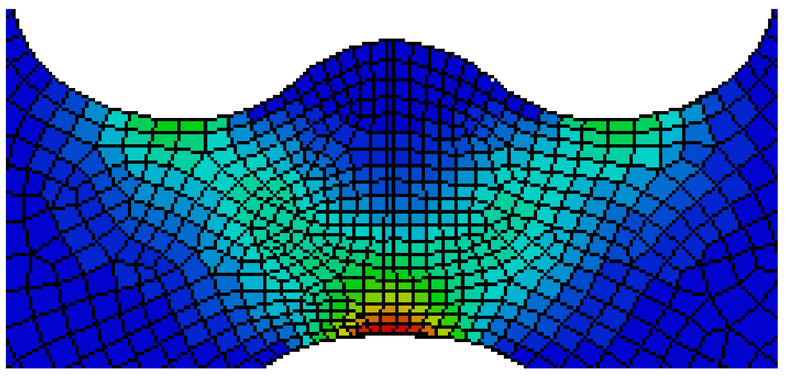

Figure 3: Magnification of the highlighted region in Fig. 2

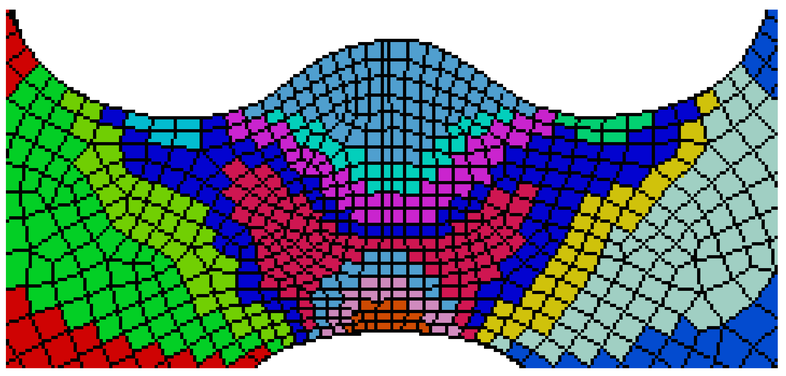

Figure 4: Position of the clusters constructed according to the accumulated plastic strain field at the final state of the simulation

Results

Test case: specimen in Fig. 2

- improved HMS that exploits clustering, vs.
- original HMS

Approximation error metric:

for material properties

$$e_i^{\beta} = \frac{|\beta_i - \beta'_{r(i)}|}{\beta_i} \times 100\%, \qquad \bar{e^{\beta}} = \frac{1}{n}\sum_{i=1}^{n} e_i^{\beta}$$

for field values

$$e_i^{\gamma} = \frac{|\gamma_i - \gamma'_i|}{\gamma_i} \times 100\%, \qquad \bar{e^{\gamma}} = \frac{1}{n}\sum_{i=1}^{n} e_i^{\gamma}$$

$n \rightarrow$ total number of integration points in the model
$i \rightarrow$ an integration point with ID $\in \{1, 2, \ldots, n\}$
$r(i) \rightarrow$ cluster representative of integration point i
$\beta_i \rightarrow$ material property at i with original HMS
$\beta'_{r(i)} \rightarrow$ material property at $r(i)$ with improved HMS
$\gamma_i \rightarrow$ field value at i with original HMS
$\gamma'_i \rightarrow$ field value at i with improved HMS

$e_i \rightarrow$ approximation error at i
$\bar{e} \rightarrow$ approximation error for the whole model

Computational speedup: $s_c = \frac{t_r}{t_c}$

$t_r \rightarrow$ simulation time with original HMS
$t_c \rightarrow$ simulation time with improved HMS

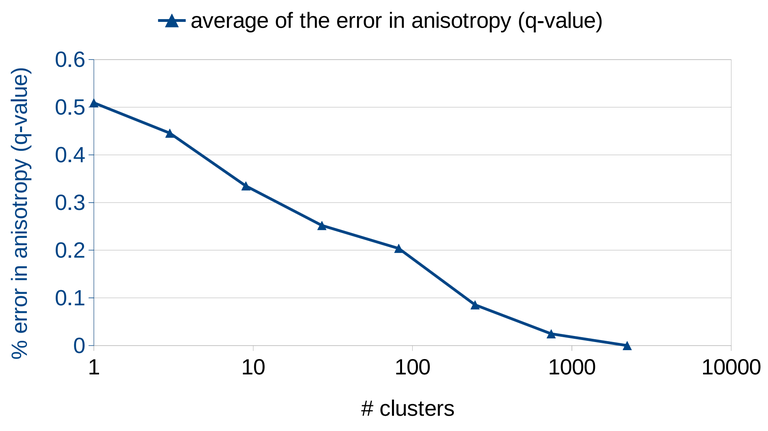

Figure 5: Accuracy in material property approximation for varying number of clusters.

Error and performance depend significantly on the number of clusters used.

Trade-off: By increasing the number of clusters

- the approximation error can be decreased, but at the same time
- the computational cost is increased

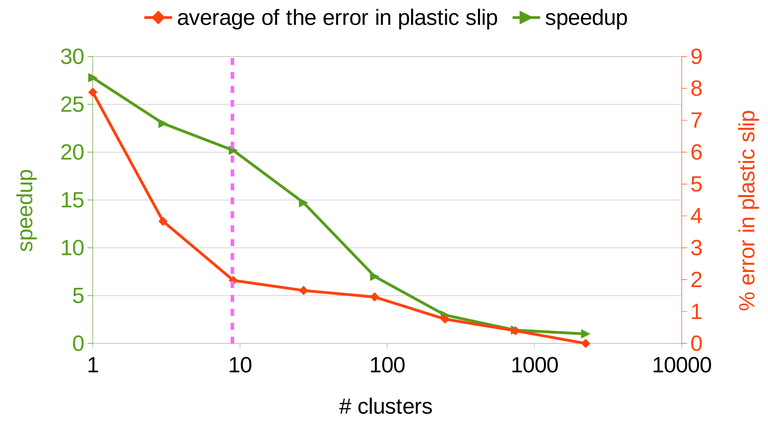

Figure 6: Speedup vs approximation error in field value. The dotted vertical line highlights a *"hot-spot"* of a high speedup with acceptable accuracy.

References

[1] J. Gawad et al., "Hierarchical multi-scale modeling of texture induced plastic anisotropy in sheet forming", Comp. Mater. Sci., 66, 65–83 (2013).

[2] F. Pedregosa et al., "Scikit-learn: Machine Learning in Python", J. Mach. Learn. Res., 12, 2825–2830 (2011).

Conclusions and future works

- The clustering approach can considerably accelerate the HMS model while retaining accuracy.
- In practical simulations the accumulated plastic strain evolves in time and clusters should adapt to this. Therefore, our future work includes the implementation of dynamic/adaptive clustering.
- As texture evolution depends on the straining mode, future work should also consider similarities of deformation increments in the clustering criteria.